Short Range Forecasting Division
Scientific Paper No. 3

Current developments in very short range weather forecasting

by

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March 1992

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Abstract

This review was prepared for the first meeting of the WMO Commission for Atmospheric Sciences Group of Rapporteurs on Short Range Weather Prediction Research, held in Bracknell in January 1992. The full report of the meeting will be published by WMO.

Very short range forecasting (VSRF) is taken to cover a forecast period of approximately 0–12h and therefore to be concerned mainly with the effects of 'mesoscale' features with length scales up to 1000km or so. The VSRF task is to provide detailed local weather forecasts and consists of making observations, interpreting them, producing the forecast, tailoring it to the user's requirements and delivering it, all within a period that may be as little as a few minutes, and then (usually) repeating this cycle. Developments and improvements are currently underway in all aspects of the VSRF process.

Considerable progress is being made in establishing new and improved observing systems and techniques, in international exchange of mesoscale observations, and in objectively combining mesoscale observations from many diverse sources. Remotely-sensed observations are of particular importance to VSRF. Weather radars and satellites have established themselves as indispensable sources of observations, and other systems, such as lightning-location networks and wind profilers, are being investigated.

Many forecasting techniques are used in VSRF, since in contrast to longer period, larger scale forecasting, the VSRF regime is not yet dominated by numerical weather prediction (NWP) models. Linear extrapolation is widely used, particularly in systems for nowcasting precipitation. Conceptual models of mesoscale phenomena are also being applied to VSRF; these can take account of non-linear development, offer means of interpreting incomplete observations, relate weather events to their precursors and allow NWP model variables to be derived indirectly from other observed parameters. Forecasting methods differ in their strengths and weaknesses so that no one technique is suitable for all weather situations and timescales. Attention is therefore being given to integrated forecasting systems that combine different methods in an adaptive, situation-dependent way, so as to use the various forecast methods to their best advantage. Adequate objective verification techniques are important for both the development and operation of such systems.

Facilities at forecast offices are being improved to allow forecasters access to, and means of displaying and processing, the rapidly increasing range and volume of data, and to help them assemble and disseminate forecast products. At the same time, efforts are being made to apply automation, including the use of artificial intelligence techniques, to all stages of the VSRF process.

Convective storms and their associated weather events are the largest single VSRF preoccupation. Conceptual models are being used to help understand and forecast them and work is underway to develop suitable, very high resolution, numerical forecast models. Some important convective phenomena, such as microbursts, can be predicted only minutes ahead and present perhaps the severest test of operational VSRF techniques and systems.

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Current developments in very short range weather forecasting

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1 Introduction

This paper is a review of current developments in very short range forecasting (VSRF), prepared for the first meeting of the WMO/CAS Group of Rapporteurs on Short Range Weather Prediction Research, held at the Meteorological Office, Bracknell, from 13 to 17 January 1992.

VSRF is taken to cover a forecast period of approximately 0–12h and therefore to be concerned mainly with the effects of 'mesoscale' features with length scales up to 1000km or so (Bodin, 1983). VSRF includes a 'nowcasting' subrange, the period of validity of forecasts based on a detailed description of the current situation and extrapolation from it using observed trends. This is commonly taken to be roughly 0–2h but varies greatly, from a few minutes to several hours, depending upon the weather situation.

Thorough reviews of VSRF and related topics by other authors already exist. Bodin's 1983 review for WMO discussed observational requirements and systems, forecasting methods and examples of experimental and operational VSRF systems. The wide-ranging book edited by Ray (1986) contains some 31 chapters on different aspects of mesoscale meteorology. More recently, Browning (1989), in his presidential address to the Royal Meteorological Society, described a range of forecasting methods and the observational techniques contributing to the 'mesoscale database' upon which the forecasts depend. The review by Browning and Collier (1989) focuses on nowcasting precipitation.

The scope and historical development of VSRF are well-covered by these and other reviews. The more limited purpose of this paper is to draw attention to those developments and issues that appear to be most significant for VSRF now and in the next few years. Examples and references (including some from outside VSRF as defined above) are given to illustrate the topics discussed, but they do not by any means constitute an exhaustive survey. The review is inevitably a personal perspective; other authors might well emphasize different aspects and include different examples.

The review starts with an outline of developments in observing systems for VSRF, concentrating on remotely sensed observations without which many VSRF tasks would be impossible. The next section is concerned with forecasting methods. Many forecasting techniques are used in VSRF, since in contrast to longer period, larger scale forecasting, the VSRF regime is not yet dominated by numerical weather prediction (NWP) models. Various forecasting methods are discussed and examples presented of their ap-

plication. High-resolution NWP models are beginning to demonstrate useful capabilities in the VSRF regime, but they are mentioned only briefly here: a thorough review of developments in limited area modelling is given by Bougeault (1992). The review continues with a section on means of carrying out VSRF, that is of actually applying the various forecasting techniques previously discussed. Part of this section deals with improvements in interactive facilities at forecast offices, and the rest discusses efforts to automate VSRF tasks, including the use of artificial intelligence techniques. The review then says something about the application of VSRF to 'extremely short range forecasting', in which the whole VSRF process, including delivery of the forecast to the user, is compressed into a few minutes in order to give brief but useful warning of a dangerous event such as a microburst or tornado. The review concludes with some remarks about the importance of systematic verification and assessment of VSRF.

Sources for this review include papers in journals, proceedings of recent conferences and information supplied by a number of correspondents, active in the field of VSRF, from various parts of the world.

2 Observations

Because of the spatial scales and rates of change of the mesoscale features being studied, observations for VSRF must have high spatial and temporal resolution and (ideally) uninterrupted areal coverage. They must be delivered quickly and updated frequently. Hourly observations from the traditional surface networks are hopelessly inadequate for this task and VSRF depends heavily upon remotely sensed observations, from both satellites and ground-based systems. The value of weather radar observations and satellite imagery for VSRF is well-established, and lightning-location systems and wind profilers are being investigated as tools for VSRF. The picture is one of sustained growth and innovation, with new systems being installed and existing systems improved. Significant developments in some of the more important types of observing system are outlined below.

2.1 Weather radar

Weather radar has established itself as the primary observational tool for many VSRF applications, particularly within nowcasting. For a comprehensive review of the use of radar in meteorology and hydrology see the book by Collier (1989).

Ground-based weather radar systems are being installed, enhanced and expanded in many countries. Coverage is being extended, analogue systems are being replaced with digital ones, and advanced measurement techniques, particularly Doppler radar, are being employed or investigated. New radar products and ways of presenting and using them are being developed and evaluated, as are algorithms for automatically interpreting and extrapolating radar observations. International exchange of weather radar data in near real-time has been established.

The largest single weather radar programme is NEXRAD (NEXt generation weather RADar), a major programme designed to provide essentially complete Doppler radar coverage of the continental United States within the next few years (Golden, 1990; Alberty

et al, 1991).

The network will be based on the WSR-88D, a Doppler and reflectivity radar capable of measuring reflectivity to a range of 460 km and radial velocities and spectrum-width to 230 km. The radars have sufficient sensitivity to detect, more reliably than existing operational radars, low reflectivity clear-air features such as convergence lines.

Comprehensive interactive display facilities are provided to allow forecasters to examine mesoscale weather systems and recognize significant features. Specific algorithms have been designed to interpret the radar data automatically, in order to recognize significant features or events, and in some cases to generate short-term forecasts. Examples are algorithms to recognize mesocyclones and tornadic vortex signatures, and the 'storm sequence' set of algorithms that attempts to identify, track and extrapolate the positions of thunderstorm cells. Work continues to evaluate and improve these algorithms (e.g., Albers, 1991; Schudalla and Smart, 1992).

Radar systems providing only reflectivity measurements are adequate for many tasks and have formed the basis of successful nowcasting operations, but there is widespread interest in the additional capabilities of Doppler radar, not only in countries prone to severe tornadic storms. Thus in the UK, a network of reflectivity radars has been used for nowcasting precipitation since the early 1980s; starting in 1992, experiments will be conducted with Doppler radar at selected sites.

Crozier *et al* (1991) describe experience of using Doppler radar in a combined research and operational facility at King City, north of Toronto. The Doppler facility proved useful in many situations in which reflectivity products alone were inadequate, for example: detection of mesocyclones with tornado potential; mesoscale analysis within synoptic-scale storms; anomalous propagation and clutter removal; clear-air echoes and lake-effect breezes; lake-effect snow squalls from shallow convection.

The benefits of Doppler radar are now well-established. Other advanced radar techniques are being investigated but have yet to prove their worth for operational weather forecasting. The relative merits of various techniques are discussed by Randeu (1990).

The COST 73 programme[1] (Newsome, 1992) has demonstrated the feasibility of producing and disseminating international rainfall radar composites on a routine operational basis. Radar data from the national networks of participating European countries are transmitted to the UK Meteorological Office, Bracknell, where they are assembled into hourly composites; these are combined with locally received Meteosat IR (infrared) cloud information and disseminated to member countries.

The primary objectives of the COST 73 programme have been to foster the establishment of *operational* weather radar networks in the signatory countries and to harmonize operations, data handling and processing to facilitate and exploit the international exchange of weather radar data. The programme has produced outline specifications and requirements for hardware and software systems for radar sites and network centres and for display facilities.

It is estimated that by the end of the COST 73 programme in 1991 there were about 80 operational radars in the COST 73 countries, of which 35 had a Doppler facility. The

[1]COST = European Cooperation on Science and Technology.

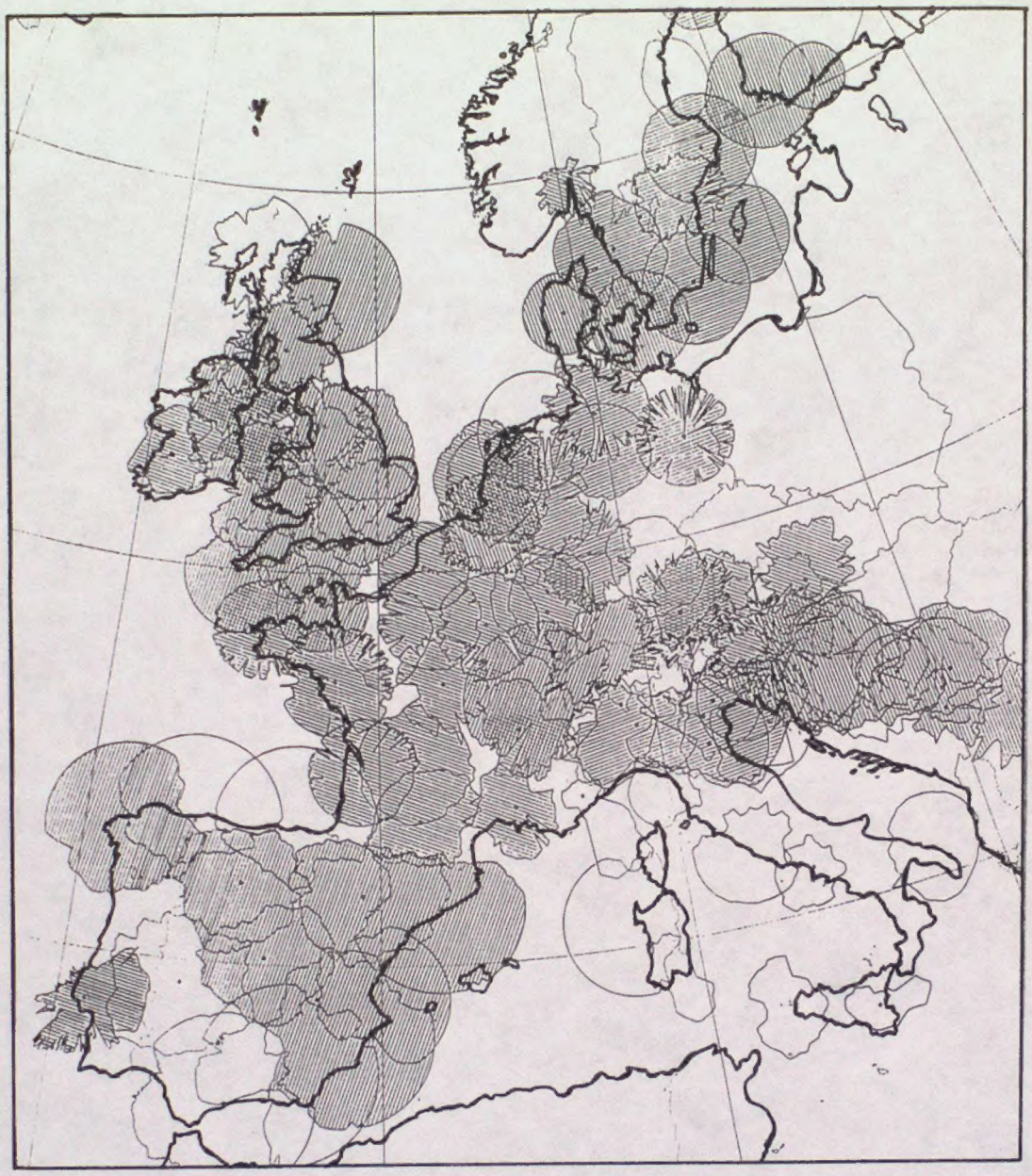

Figure 1 *Expanded area for COST 73 European radar composites. Radar boundaries show coverage at a height of 1500m. Shaded regions show radars in place during 1991; unfilled boundaries show installations expected by 1993. (Newsome, 1992).*

number is expected to grow to 111 by 1993, 44 with Doppler. The growth in the deployment of operational radars is prompting the expansion, later in 1992, of the COST 73 radar composite area to that shown in Figure 1.

Progress in establishing and exploiting weather radar systems is being made in many parts of the world; the above examples serve merely as illustrations. Latest developments are presented at conferences such as those cited in the reference list at the end of this review, particularly the biennial Conference on Radar Meteorology sponsored by the American Meteorological Society. Descriptions of a number of national weather radar projects, in Europe and elsewhere, are to be found in Collier and Chapuis (1990).

2.2 Satellite observations

Satellites have become an essential source of observations for VSRF, and for nowcasting in particular; Browning (1989) describes a number of applications in mesoscale meteorology. However, satellites provide only indirect measures of many of the variables of interest, the derivation of which can be a difficult and uncertain process.

At present, satellites provide two main types of product for use in forecasting: vertical soundings of temperature and humidity, and images recorded at various visible and infrared wavelengths.

Soundings are mainly used in large or medium scale NWP models and are discussed by Lynch (1992). For VSRF, particularly for nowcasting, interest centres on image-data, which may be used in a number of ways:

- more or less direct, point by point, measurement of some physical quantity such as sea-surface or cloud-top temperature;
- classification of cloud-types by their spectral or textural characteristics (Eyre *et al*, 1984; Karlsson and Liljas, 1990);
- identification and classification of significant meteorological entities, such as fronts or convergence boundaries, from their composition and shape; appropriate conceptual models provide the means to relate the forms observed in satellite images to the underlying atmospheric processes (Purdom, 1982; Bader *et al*, 1992);
- estimation of secondary quantities, for example precipitation fields from multispectral cloud radiance data (Lovejoy and Austin, 1979), or winds from cloud motion vectors;
- relating imagery to NWP model variables via conceptual models (Wright and Golding, 1990);
- checking the progress of an NWP forecast by comparing the observed cloud features with those expected from the model (Smith *et al*, 1988).

Imagery is available from both polar-orbiting and geostationary satellites. Polar orbiters provide the most detailed observations. NOAA (the US National Oceanic and Atmospheric Administration) maintains two such meteorological satellites orbiting at an altitude of about 850km, which provide imagery from the Advanced Very High Resolution Radiometer (AVHRR) instrument. The AVHRR has five spectral channels in the infrared and visible bands at a resolution of about 1km at the sub-satellite point.

The fine detail of the AVHRR imagery enables small cloud features to be detected and reveals cloud texture but, except in polar regions where successive orbital views overlap, the polar orbiters have the serious drawback, for VSRF, of providing only infrequent observations at any given location.

For this reason it is the geostationary satellites that are of greatest value for nowcasting and for VSRF applications requiring frequent updates. There are five geostationary satellites providing meteorological data from equatorial orbit. There are normally two US GOES (Geostationary Operational Environmental Satellites), at about 75°W and 135°W

respectively, the European meteorological satellite, Meteosat, near 0°, the Indian satellite, INSAT, near 80°E and the Japanese GMS (Geostationary Meteorological Satellite) at 130°E. Together they provide worldwide coverage, apart from polar regions. For further details see, for example, Szejwach (1990) and WMO (1990).

Meteorological satellite programmes continue to evolve, with many of the improvements, particularly for geostationary satellites, driven by the needs of nowcasting and VSRF. A recent workshop on the use of satellite data for VSRF (EUMETSAT, 1990) stressed the need for continued improvements in spatial resolution, repetition rates, and the number of spectral channels. Images comparable in quality with those from the AVHRR instrument on the NOAA polar orbiters are needed for the most demanding applications, such as the early detection of convection.

Major enhancements are planned to both the GOES and Meteosat series of geostationary satellites.

Gird and Shenk (1991) describe NOAA's plans for the GOES series of geostationary satellites. Starting with GOES I to M (planned for initial launch in 1992) the imager will have a 1km resolution visible channel, three 4km IR channels and a 6.7μm, 8km WV (water vapour) channel, providing full-disc scans every 30 minutes with the option of using part of the time for 5-minute scans of small areas of particular interest (Koffler and Spayd, 1991). Atmospheric soundings will be available from a separate instrument. GOES-N onwards, which will follow, will incorporate various improvements, including a second imager and more spectral channels.

Meteosat Second Generation (Morgan, 1990), the new version of the European geostationary satellite, is due for launch towards the end of the decade. For VSRF, the most significant enhancement will be a much improved imager, with 8 channels, mostly at 3km resolution at the sub-satellite point but including a 1km visible channel.

Additional channels and/or improved spatial resolution are also planned for the GMS and INSAT series of satellites over the next few years (WMO, 1990).

The NOAA series of polar orbiters will continue, with periodic enhancements (see Needham, 1991). After NOAA-L, due for launch in 1996, NOAA will provide only one of the two polar orbiters, the other being flown, with a similar instrument package, by EUMETSAT.

2.3 Lightning detection and location systems

Measurements of the position and time of occurrence of lightning flashes are useful indicators of convective activity, particularly in conjunction with other observations such as radar echo-intensity maps (Goodman, 1991) or satellite IR imagery (Rust, 1991). Additional information, such as the polarity of strokes, number of strokes per flash, and whether a discharge is cloud-to-ground or cloud-to-cloud, may provide clues to the state of development of the convective system and its likely evolution.

Automatic ground-based lightning-location systems rely upon detecting the electromagnetic emissions from lightning strokes. Various methods are employed: direction-finding and triangulation (Orville *et al*, 1983; Scott, 1988), accurate comparison of the time of arrival of the signal at several stations (Bent and Lyons, 1984; Lee, 1986), and

VHF interferometry (Richard *et al*, 1989).

Interpretation of the measurements is not always straightforward: errors in position and timing can occur and the probability of detection may be low and uncertain. Not all the parameters mentioned above may be measured. Nevertheless, lightning-location data are likely to be a useful source of evidence for VSRF, given appropriate conceptual models within which they can be interpreted.

Optical detection of lightning from space has been demonstrated, and plans exist to fly an instrument for this purpose on a NOAA geostationary satellite by the late 1990s. The instrument will detect both cloud-to-ground and cloud-to-cloud flashes; it is expected to have a horizontal resolution of about 10km and a detection efficiency of about 90% (Christian *et al*, 1989).

2.4 Wind profilers

Wind profilers are near-vertically pointing radars designed to measure the vertical wind profile of the atmosphere using Doppler techniques. Existing installations are experimental but operational networks of profilers are likely to be introduced within the next few years.

In Europe, wind profiler development is being coordinated within the COST 74 project, which was started in 1987 and will continue until 1993 (Gilet and James, 1991). The role of COST 74 is to foster cooperation; individual countries in Europe will continue to pursue their own R&D on wind profilers.

The main objective of COST 74 is to coordinate European R&D activity aimed ultimately at the deployment of a Europe-wide network of profilers. Particular issues being addressed are the establishment of a user-requirement, allocation of internationally agreed radio-frequencies and standard specifications for both systems and data. The installation of between 100 and 500 systems in Europe is envisaged during the next decade.

Serafin and Dabberdt (1990) provide a critical review of wind profilers and discuss plans for their introduction and use in the USA. A demonstration network of some 30 profilers operating in the region of 400MHz is being installed in the central United States by NOAA's Forecast Systems Laboratory (FSL) with further units for specific investigations.

Radio frequency allocations in three frequency bands, near 50, 400 and 1000 MHz, are being sought for wind profilers. The higher frequencies offer improved vertical resolution whereas the lower frequencies provide greater vertical range. Thus systems at around 1000 MHz are limited to perhaps the lowest 3-4 km but are good for resolving detail within the boundary layer and thus for pollution applications, while systems at around 50 MHz can provide observations to 30 km and beyond, albeit with poorer vertical resolution. Dual frequency systems may offer a way of providing the advantages of both. A significant practical problem is that some of the frequency bands sought are already occupied by important operational applications.

RASS (Radio Acoustic Sounding System) is an extension of the profiling technique that allows the temperature structure of the lower atmosphere to be measured by transmitting an acoustic wavefront upwards and detecting its progress using a profiling radar

(Peters, 1990). The system measures virtual temperature, so knowledge of the humidity profile is required to recover actual temperatures and observations of inversions tend to be degraded.

Wind profilers can provide observations with excellent temporal resolution, but the horizontal coverage of any realistic wide-area network of profilers is likely to remain (in VSRF terms) sparse. However, studies at the US National Severe Storms Laboratory (Rust, 1991) have shown that wind profiler data can usefully complement profiles derived from NEXRAD radar measurements by extending their height. The introduction of profilers is likely to benefit VSRF in two main ways. Local installations at sensitive sites such as airports may provide data directly for very short range warnings, while the assimilation of high temporal resolution wind data into numerical analysis schemes and models will provide a more complete and detailed picture of the atmosphere for use by a range of VSRF techniques.

2.5 Automatic weather stations (AWS)

In general, ground-based weather stations making local observations cannot satisfy the needs of VSRF for high-resolution coverage in both space and time, and VSRF will therefore always depend largely on remotely sensed observations with wide areal coverage, whether from ground-based or space-borne instruments. Wilson and Mueller (1991) have shown that even with a dense network of AWS, the conditions governing the onset of some convective events may be too finely balanced to be determined from the AWS observations alone.

AWS can, however, provide frequent reports, and can be valuable as means of checking and calibrating remotely sensed observations such as radar precipitation measurements. The Japan Meteorological Agency operates AMeDAS, a network of some 1300 AWS with a mean spacing of 17km, and uses its observations in conjunction with those from weather radars to analyse and nowcast precipitation (Segami, 1989; Hirasawa, 1991).

It is possible to set up limited area arrays of AWS either for experimental or operational purposes, though wide-area coverage at a useful density for VSRF becomes prohibitively expensive. NOAA's FSL has established a dense 'mesonet' of some 22 AWS which can provide observations at frequent intervals and which is used in various forecasting experiments, and in Sweden, the PROMIS 600 VSRF system (see §4.1.3) uses data from a dense local network of 40 AWS for operational weather forecasts. Some networks are designed for a specific task and may measure a single parameter: the low level wind shear alert system (LLWAS) (Wilson and Gramzow, 1991) is an arrangement of anemometers deployed at a number of US airports to detect wind shear hazards.

2.6 Combining observations from various sources

Although some nowcasting tasks may be based upon a single source of observations, such as weather radar, in many VSRF applications contributions from a number of different sources may be combined to advantage.

Since 1987, FSL has been developing 'LAPS', a Local Analysis and Prediction System (McGinley *et al*, 1991), which objectively assembles high-resolution 3-D mesoscale analy-

ses from a wide variety of sources, for use by any VSRF technique. The idea is to present a series of snapshots containing as detailed and complete a picture as possible of the state of the atmosphere over a limited region. At present LAPS produces hourly updates on a grid of spacing 10km horizontally by 50hPa vertically, though more frequent updates are envisaged. Input data sources include Doppler radar, wind profilers, the FSL mesonet, GOES images and soundings, rawinsondes, aircraft and pilot reports, and conventional hourly surface observations. The analyses include 3-D cloud distribution, temperature and moisture fields, horizontal winds and estimated vertical motion, and various derived parameters and indices. LAPS is a study of the feasibility and value of combining the sorts of mesoscale observations that will become increasingly available to regional forecast offices in the US and elsewhere. It has been applied in experiments to nowcast snowfall (Chappell and Schultz, 1991) and radar echo patterns (Jackson *et al*, 1992), and comparisons have been made of the forecast quality with and without LAPS analyses. Results are reported to be encouraging, particularly in the early part of a forecast period, but clear statistical evidence of the overall benefit of LAPS is still awaited. LAPS may still be too coarse in both spatial and temporal resolution for some nowcasting applications but it is nonetheless providing valuable experience in the problems of combining and using diverse mesoscale observations.

3 Forecasting

Many forecasting techniques (linear extrapolation, NWP models, statistical methods, conceptual models, decision trees, etc.,) are used in VSRF. Each has its strengths and weaknesses; the choice of method depends upon the event being forecast, the observations available and the tools available at the forecast office. Some of the commonly used methods are outlined below and examples of their use are cited or briefly described.

3.1 NWP models

Considerable effort is being put into developing NWP models capable of resolving the mesoscale features important for VSRF, and mesoscale NWP models with grid spacings of a few kilometres are beginning to find their way into operational forecasting suites. Difficulties still exist however in supplying high-resolution models with suitable observational data and in making the best use, via appropriate initialization and assimilation schemes, of those observational data that are available. For reviews of recent developments in limited area models and data assimilation see Bougeault (1992) and Lynch (1992) respectively.

Mesoscale models with grid spacings of several kilometres may give adequate representations and predictions of features such as rainbands and sea breezes, but they cannot depict smaller entities such as severe convective storms, which are nonetheless of great significance and impact as weather events. Such events demand a grid spacing of order 1km or less and observations at similar resolution. The Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma has embarked upon a programme to develop a system, incorporating a very high resolution model and assimilation scheme, capable of predicting new thunderstorms to 3h ahead and to within a few miles, and the

evolution of existing storms to about 6h ahead (Lilly, 1990; Drogemeier, 1991). Prodigious computing power is demanded but is expected to be available, along with appropriate observations, at regional forecast offices by the mid to late 1990s.

3.2 Linear extrapolation

Linear extrapolation is the simplest and most obvious short-period forecasting technique taking account of current observations (if we include persistence as the special case of zero rate of change). It is widely used in VSRF, particularly in systems for nowcasting precipitation.

The range of validity of linear extrapolation is limited by the non-linearity of the phenomenon being forecast and the acceptable forecast error (Doswell, 1986). It varies considerably with the type of phenomenon and, for a given phenomenon, from case to case. A fundamental limitation of the method, particularly serious in convective situations, is that it cannot cope with the development of new events not present in the initial observations.

Use of the technique depends upon (a) having a sequence of high quality observations of the parameter of interest and (b) being able to measure the change in that parameter between successive observations. The change being measured is often that of the position of some feature, such as an area of rainfall. Since such features are continually evolving and changing shape the measurement (and even a precise definition) of their movement presents many difficulties.

Centroid-tracking (Wilk and Gray, 1970) and related techniques involve isolating features to be tracked and identifying them correctly in successive images; this is often a non-trivial problem, but the method can be successful in suitable situations such as isolated convective storms. Cross-correlation (Austin and Bellon, 1974) simply measures the displacement that gives the best match between two successive image-fields (not individual objects) and tends to be most successful with larger meteorological features (Austin and Bellon, 1982). A discussion of the basic methods and some of their variants can be found in Chapter 6 of Collier (1989).

The process can be modified to measure and extrapolate development or decay, though such elaborations have been reported to yield little benefit (Tsonis and Austin, 1981).

In spite of its limitations, linear extrapolation can provide successful short-term forecasts in a range of situations and forms the basis of a number of well-established VSRF systems, examples of which are outlined below. The systems described have many similarities but also exhibit an interesting variety in their choice of data sources, degree of automation, means of calculating the forecast, etc.

3.2.1 RAINSAT

The RAINSAT system developed at McGill University in Canada (Austin and Bellon, 1982; Austin *et al*, 1990) combines precipitation and echo-top measurements from weather radars with imagery from geostationary satellites to generate composite maps of precipitation. Precipitation maps are derived from visible and infrared satellite data using

statistical classification based on previously calculated correlations between collocated radar and satellite observations. Radar observations of precipitation, where available, are overlayed on the satellite-derived maps. Movement of the rainfall is estimated using cross-correlation of successive rainfall maps, and short-term (1–6h) forecasts are produced by linear extrapolation, though synoptic steering wind velocities may also be used. Nevado (1990) describes the installation in Spain of a RAINSAT system ('SIRAM') which uses a network of 13 radars and imagery from the Meteosat satellite.

3.2.2 FRONTIERS

At the UK Meteorological Office, an interactive image processing system called FRONTIERS (Browning, 1979) is used to produce, every half hour, quality-controlled current rainfall maps and a series of hourly extrapolation forecasts for up to 6 hours ahead, on a 256×256 5km grid covering the UK. The products are based on data from a network of reflectivity radars, together with visible and infrared images from the Meteosat geostationary satellite.

FRONTIERS comprises three main stages (Conway and Browning, 1988): (a) preparation of a quality-controlled radar rainfall analysis, (b) incorporation of Meteosat data to extend the area of coverage, and (c) generation of the forecasts. All these functions are performed by or under the direct control of an experienced forecaster, although FRONTIERS incorporates many algorithms to facilitate the task and to perform the calculations required.

The original (and still used) method of producing the forecast was for the FRONTIERS operator first to segment the rainfall analysis (using the interactive facilities provided) into rainfall clusters and then to estimate the velocities of the clusters by replaying sequences of the most recent analyses. The forecasts were then calculated by linear extrapolation of the cluster movement, incorporating corrections for orographic effects and an optional development/decay factor.

More recently, the forecaster has been given the additional option of choosing forecasts calculated automatically by moving the observed rainfall along trajectories calculated from forecast wind fields at roughly 850 and 700mb (Brown *et al*, 1991) provided by the Meteorological Office's mesoscale NWP model (Golding, 1990).

A much greater degree of automation is now planned (Sutton and Conway (1990) suggest a possible scheme) and it is likely that nowcasts and very short period forecasts of precipitation will be generated entirely automatically in due course.

3.2.3 Precipitation nowcasting in Japan

The Japan Meteorological Agency (JMA) produces hourly analyses and very short range forecasts of precipitation on a 250×660 5km grid covering the whole of Japan. These products are generated by a totally automated system at JMA headquarters and forecasts are available within 20 minutes of observation time (Segami, 1989; Hirasawa, 1991).

Observations are taken from a network of 20 weather radars measuring echo-intensity and echo-top height, the AMeDAS network of about 1300 automatic surface observation stations, and the GMS-4 satellite, which provides hourly visible and infrared images.

Forecasts are produced by linear extrapolation of radar echo movement. Motion vectors are derived by cross-correlation, first for the entire area then for sub-areas. Stationary echoes are identified and removed from the extrapolation procedure and then the non-stationary echoes are moved at the measured velocities, corrections being applied both for orographic enhancement by the feeder-seeder effect and for dissipation of rain in downslope regions. Wind and temperature data from the Japan Spectral Model (JSM) are used for these calculations. When cross-correlation velocities are unavailable, 700mb winds from the JSM are used. Forecasts of echo-intensity are made for 10 minute intervals up to 3 hours ahead, enabling hourly accumulations to be calculated.

The main products from the analysis and forecasting system are a composite radar echo chart, a radar-AMeDAS analysis chart showing 1-hour precipitation accumulation, and forecasts of hourly precipitation accumulations up to 3 hours ahead. Many other forecast products for specific applications are derived from the basic echo-intensity and accumulation predictions.

3.2.4 METEOTREND

The METEOTREND project at the Slovak Hydrometeorological Institute (SHMI) in Czechoslovakia is designed to make extrapolation forecasts of clouds and thus of associated weather phenomena for up to 2 hours ahead on a grid of resolution 8km over an area of 1000km×1000km. (Podhorsky, 1987, 1991)

METEOTREND is based on Meteosat images at hourly or half hourly intervals. Cloud types important for the user (aviation) are defined and related to 'feature vectors' whose elements consist of values derived from aerological and surface data and from Meteosat IR and WV images. The system is partly interactive, allowing a meteorologist to choose subjectively parameter-values best suited to a particular case. The system identifies objects of interest by the similarity of their feature vectors to those of individual archetypes. Once identified the features are tracked in successive images and their movement and rate of vertical development are estimated and projected forward to produce a forecast. Alternatively the 'advective-convective tendencies' derived may be displayed on a colour screen for the information and guidance of a meteorologist. Work is underway at SHMI to apply similar techniques to radar data (Podhorsky, 1991).

3.3 Conceptual models

A conceptual model (see, for example, Browning, 1986) is an idealized qualitative or semi-quantitative description which incorporates an understanding of the structure, mechanism and life cycle of some meteorological phenomenon. As a tool for VSRF, the conceptual model overcomes a limitation of linear extrapolation by providing a description of the evolution of the phenomenon, including its non-linearities.

Phenomena at any scale may be represented in this way, the frontal analysis of surface charts providing a familiar example on the synoptic scale. The assignment of a name to a phenomenon (e.g., polar low, cold front, mesocyclone) implies its recognition as an entity with characteristic properties and thus the existence of a conceptual model, though the detail and complexity of such models vary widely.

Quantitative physical understanding of the model or its components is useful in providing internal constraints so that a complete and consistent picture can be built up from flawed or incomplete observations. Such an understanding can help the subsequent evolution of the phenomenon to be predicted in a quantitative as well as a qualitative way. Quantitatively based conceptual models can also enable observations such as satellite imagery to contribute to the initialization of NWP models, by relating observed cloud features to model variables (e.g., Wright and Golding, 1990).

A major difficulty in applying conceptual models lies in fitting them to actual observations. Because the model is an idealization, real instances of the object represented by it will invariably depart from the archetype. As well as exhibiting quantitative variations, the real instance may lack individual components of the model, or incorporate additional features, or be complicated or obscured by neighbouring phenomena. The identification and matching process must take account not only of the expected features of the phenomenon, but also how they will be portrayed by imperfect sensors and observing systems.

This matching task is an essential part of the job of a human forecaster in making sense of the observations he is presented with, but it can still be an uncertain process, for example in the exact placing of a front on a surface analysis. Efforts are now being made to represent and recognize conceptual models in automatic systems (e.g., Sénési *et al* (1990), Hand (1991)).

The development and application of appropriate conceptual models is proving particularly important in understanding and interpreting radar observations of convective storms, so as to identify precursors of sudden, hazardous weather events such as microbursts (Roberts and Wilson, 1989) and tornadoes (Wilson and Roberts, 1990) and to develop automatic systems for this task (Campbell, 1988).

3.4 Statistics

Weather events may be connected in a purely statistical way, i.e., without any causal mechanism being postulated, to observations at an earlier time, or to parameters predicted by an NWP model. For a discussion of some of these methods and their relative merits see Wilson (1989, 1992).

An example of the use of such techniques for VSRF is the 'SHORT' program developed by the Canadian Atmospheric Environment Service (AES). SHORT is a classical REEP (Regression Estimation of Event Probabilities) program (Wilson and Sarrazin, 1989) that produces forecasts of ceiling height, visibility, weather and obstructions to vision, wind direction and speed, and total cloud amount for individual stations, at projections of 2, 4, 6 and 8 hours. Forecasts can be run at any time, the only input required is the last two hourly observations at the station where forecasts are desired. The statistical forecast equations are based on up to 32 years of hourly station observations (depending upon the length of record at the station), and essentially describe the climatology of trends in the local weather at the station. The latest version runs on an IBM XT microcomputer and is available at 17 stations in four different regions in Canada.

An example of an automatic system based on statistical forecasting but including other techniques is 'MEZOMAP1', being developed at the Institute of the Physics of the

Atmosphere at the Czechoslovak Academy of Sciences to make 6h and 12h forecasts of summer convective phenomena (Podhorsky, 1991). It depends on deriving and applying statistical connections between various sources of data (predictors) and the events to be forecast (predictands). The predictors are climatological characteristics of the study region, meteorological observations, and output from NWP models and other prognostic procedures.

3.5 One-dimensional models

One-dimensional air-mass transformation (AMT) models can be used to predict the evolution of the vertical structure of the boundary layer in order to make site-specific forecasts of, for example, fog or low cloud, without requiring the large computing resources of a full 3-D NWP model with comparable vertical resolution in the boundary layer.

AMT models can be used successfully at local forecast offices with only modest computing resources if trajectories from an NWP model and a good observation of the vertical temperature and humidity profile upstream are available.

Difficulties can occur with AMTs when the flow is from data-sparse regions or when the assumption that the boundary layer processes do not significantly perturb the overall mesoscale flow breaks down.

Maryon and Martin (1991) have extended an AMT developed by Reiff *et al* (1984) to provide station-specific forecasts of cloud-base and other parameters, based on weighted radiosonde ascents (modified interactively if necessary) in an upstream region. A forecast package running on a microcomputer will start trials at four UK stations in April. A single forecast takes only about 2 minutes to run so it is easy to perform sensitivity tests by rerunning the model with adjusted parameters. Seo and Smith (1990) have incorporated a model using vertically integrated liquid water (VIL) in a scheme for short-term rainfall prediction, and Gollvik and Omstedt (1988) describe an AMT used to predict boundary layer variables in the Swedish 'PROMIS 600' VSRF system.

3.6 Climatology

Mesoscale climatology can be used to help with VSRF by indicating preferred patterns of events in various weather regimes, due to the effects of local modifiers such as topography or surface composition (e.g., Monk, 1987). It may also aid interpretation of observations for VSRF by, for example, revealing areas prone to echoes caused by anomalous radar propagation (Goddard and Conway, 1991).

In most cases, the climatological effects are conditional upon the interaction of the local topography with, for example, the airflow in particular wind directions, so that at least a qualitative knowledge of the underlying physical mechanism is useful in extracting the climatological signal and applying it to best effect.

3.7 Rules and decision-trees

Empirical rules are often applied by experienced forecasters, their justification being that they produce useful results. They lack a rigorous quantitative foundation and may even be applied in a subconscious way by individual forecasters, based on personal local experience, or they may be documented explicitly. Physical rationalization of a rule may follow its initial emergence as a description of an observed relation between events.

Rules may alternatively be the distillation, for practical forecasting purposes, of the results of theoretical or experimental studies of an atmospheric process.

Collections of rules may be chained to form decision trees to forecast and discriminate among families of weather events. Colquhoun (1987) has applied the method to forecasting convective storms and associated phenomena such as tornadoes and microbursts.

The Swiss Meteorological Institute uses a mixture of manual and automatic techniques to make very short range forecasts of phenomena of local importance (Rauh, 1991). Many of the manual forecasting tasks have been formulated systematically so that the forecaster is guided by a decision tree or flow chart. Particular concerns are winds (including foehn-effect winds), snow, and the formation and clearance of fog and low cloud.

Plans exist at the SMI for more computer assistance in the handling of observations and in the preparation and distribution of forecasts, with close cooperation between man and machine. In principle, the decision trees could be coded directly as computer programs, but a degree of subjective judgement is often required to answer the questions posed and full automation is not therefore always straightforward.

3.8 Integration of forecasting methods

Individual VSRF tools (e.g., linear extrapolation, conceptual models, NWP models) have tended to be developed and applied separately, often for specific forecasting tasks. They have different strengths and weaknesses so that no one method is suitable for all weather situations and timescales. Schematic diagrams such as that at Figure 2 are familiar expressions of this situation.

Figure 2. *Schematic diagram expressing the variation in the performance of different forecasting techniques (linear extrapolation and NWP models in this example) as a function of forecast lead time (from Austin* et al, *1987). The broken curve suggests the possible effect of optimally combining both techniques. Relative performance and time of crossover will vary from case to case so adaptive combination of forecast methods is required.*

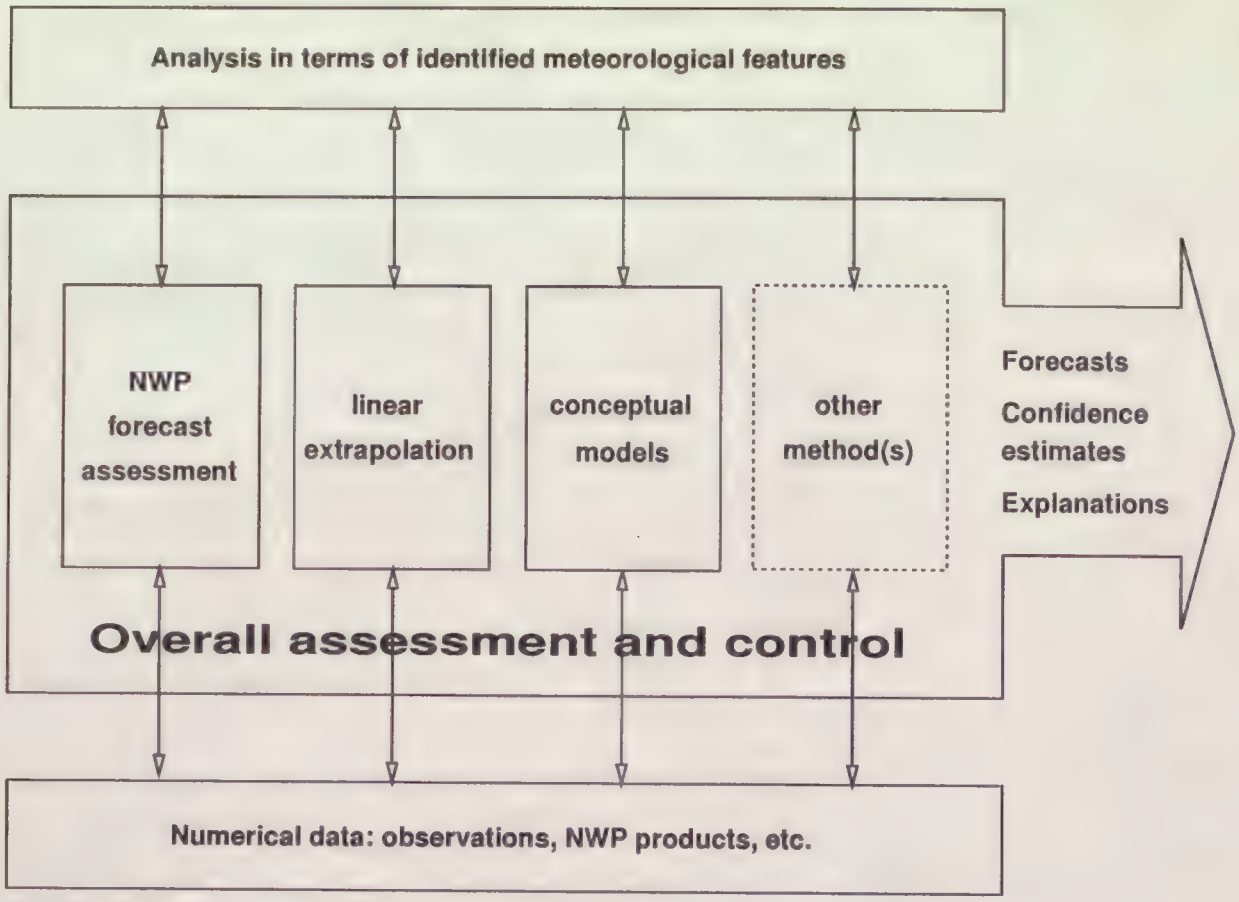

Figure 3. *Schematic diagram showing the main elements of a proposed system for adaptive, optimal integration of several forecast methods (Conway* et al, *1990). The system is extendible to include different processes or to address different forecasting problems. The meteorological analysis (top box) helps guide the way the individual processes use the numerical observations, NWP products, etc. The individual forecast processes (which also update the meteorological analysis) are any mixture of appropriate methods (see* §3.1-3.7 *and* §4.2.1*). The forecast is assembled by the control process which selects and combines contributions from the various forecast methods depending upon its assessment of their current performance.*

There is therefore a need to bring the different methods together in integrated systems so that a forecast comprises the best components on a particular occasion. Browning (1979) presented the outline of an integrated forecast system including extrapolation and NWP components.

Combining the different techniques must be done in an adaptive, situation-dependent way, since their relative values and ranges of effectiveness during the forecast period vary from one occasion to another. While it is possible to specify the kinds of weather situation to which a particular technique is usually well or badly suited, this can only act as a general guide and will sometimes fail. Moreover, more than one weather type may be present within the spatial and temporal range of a forecast sequence so that no single technique is appropriate throughout. For these reasons, choices about how to select and combine different forecast techniques must be made as the forecasts are being

prepared and issued, based on the evidence available *at that time*. This is done routinely in short and medium range forecasting by experienced forecasters who have to decide, for example, how to reconcile the guidance from different NWP models on a particular day. Similar choices must be made for VSRF techniques, whether interactively by forecasters or by fully automatic systems, if the highest quality forecast is to be produced on a given occasion. Browning (1989) describes a two-level system of workstations designed to allow a forecaster to make and apply the appropriate judgements, and Conway *et al* (1990) have proposed an outline structure (Figure 3) for a fully automated system, initially for VSRF of precipitation but extendible to other weather elements. The automatic system would continuously monitor and assess the performance of several contributing techniques, and assemble the best combination based on the evidence at the time, thus avoiding fixed rules about which technique to use. Work is currently underway on individual components of this system. Note that the success of such a system depends upon having adequate means of objectively assessing the various forecast contributions (see §6).

4 Tools and methods for implementing VSRF

VSRF makes heavy demands on the facilities at forecast offices, because of the large volume and diversity of the observational and other data to be handled, the complexity of the operations to be performed on those data, and the speed with which forecasts must be generated, tailored to the needs of users and delivered.

The response to this has been twofold: (a) to provide improved facilities (telecommunications, computer processing power and storage, display and interaction facilities) to help the forecaster cope with and make best use of the data and (b) to automate VSRF tasks where possible.

Three examples are given below of programmes to provide forecasters with improved facilities, followed by a discussion of current efforts to automate some VSRF tasks.

4.1 Improved facilities at forecast offices

4.1.1 The UKMO Weather Information System

The UK Meteorological Office (UKMO) is in the midst of a programme to modernize its facilities for disseminating observations and products to forecast offices for very-short range (and other) forecasting applications.

The new Weather Information System (WIS) comprises two parts: WIN (Weather Information Network), the communication network that will carry the data, and ODS (Outstation Display System), the combination of computers, displays and hardcopy devices that will store and present the distributed information at the forecast offices.

Until now many outstations have been dependent upon slow and inflexible facsimile and teleprinter broadcasts, in some cases augmented by special purpose displays for a particular data source such as weather radar. WIN and ODS will integrate the various distribution requirements, replace ageing equipment, reduce the cost of consumables and, most importantly, allow distribution of a wider range of higher quality data, much of

which will be perishable material, directly relevant to VSRF.

The range of data to be disseminated and displayed includes radar rainfall analyses, and forecasts derived from them; satellite imagery from Meteosat and polar orbiters, and derived products such as detected fog; NWP model products; synoptic data displayed either in map form or as a temporal sequence at a particular location; upper air data, displayed in either hodograph or T-ϕ form, or as grid-point wind data; lightning-location data and European radar data.

Display options for these data types include zooming, panning, stepping or looping through sequences, and overlaying graphical products on images. ODS is controlled by a keyboard and a cordless puck/data-tablet, and a menu system which leads novice users through the available options but which allows experienced users to jump directly to the function required.

As well as functioning as a display station, ODS incorporates various algorithms which derive secondary products, such as night minimum temperature and radar ducting, from the observational or forecast data.

Transmissions of observations, charts, binary grid point data, and radar and satellite imagery to a typical forecast office are expected to amount to about 300 Mbyte/day initially, of which 70% will be imagery. Data compression techniques are being explored and will be introduced to help cope with the expected expansion of image-based products during the 1990s.

WIN will consist of a resilient (alternative paths will by-pass a failed link) digital network operating mainly at 64kbps. An initial X400 network supporting 21 key forecast stations is expected to be implemented during 1993 with completion of the network to all stations by the end of 1994. Meanwhile, support for ODS is being provided using rented asynchronous lines operating at 9600bps. In November 1991 some 48 stations (civil and military, in both the UK and Germany) had ODS and by Autumn 1992 there should be about 90 systems installed. Availability of the full range of planned products must await establishment of the full capacity WIN.

4.1.2 AWIPS-90

The US National Weather Service (NWS) is undertaking a modernization programme intended to improve especially its VSRF capabilities. The programme includes major developments in observational, processing and presentation/dissemination facilities.

During this decade, Weather Service Forecast Offices (WSFOs) throughout the US will be equipped with AWIPS-90 (Advanced Weather Interactive Processing System for the 1990s), a system of workstations to support all operational functions in the offices.

Since 1986 a thorough prototyping exercise has been undertaken by NOAA's FSL at Boulder, CO, in conjunction with the Denver WSFO, in order to test ideas and arrive at an effective design for AWIPS-90.

In 1989 the first prototype was replaced at the Denver WSFO with a second generation system, supporting more functions and designed to overcome perceived deficiencies in the first prototype. This second system is called DARE-II (Denver AWIPS-90 Risk Reduction and Requirements Evaluation) (Bullock and Walts, 1991).

The DARE-II system receives some 3300 products daily (the National Meteorological Center will alone eventually provide more than 2000 graphical products each day). In addition to model products DARE-II receives data from satellites, Doppler radar, balloon ascents, national networks of wind and temperature profilers, automatic observing stations and lightning detection networks. These data streams are integrated and can be displayed separately or in combination, (e.g., satellite images overlayed with model graphics), singly or in repetitive loops.

Three factors have been given particular attention in DARE-II:

- performance (speed is critical in severe weather situations when warnings must be issued in a minute or less);
- the user-interface (this needs to be flexible and user-friendly and to be maintainable in the face of changes in the products to be displayed);
- reliability (99.99% reliability is required for the generation and dissemination of warnings but lower reliability can be tolerated for other functions).

A particular feature of DARE 2 is an 'almost automated' warning system that allows the forecaster to draw a warning area on the screen directly on to the data that triggered the decision, whereupon the system generates the warning message automatically.

The forecaster controls and interacts with the system via a mouse and menus and much effort has been put into making this interface fit in with the way the forecaster wishes to work, based on experience with the earlier prototype. Mouse operations are a design compromise between functionality and ease of learning. New users of DARE-11 can reportedly train themselves in 2-3 hours and there is regular liaison between users and developers.

Reliability is achieved by means of duplicated components (including power supplies) and switchable communications so that failure of an individual component cannot jeopardize critical functions.

4.1.3 PROMIS 600

The Swedish Meteorological and Hydrological Institute (SMHI) has developed a pilot station for VSRF, called PROMIS 600 (Nilsson and Brunsberg, 1990). PROMIS 600 is an interactive system that processes, combines and displays meteorological data from a wide range of sources, including Doppler weather radars, polar-orbiting and geostationary satellites, a lightning-location system and a dense network of ground-based automatic weather stations.

Objective 3-dimensional 'meso-beta' (22km grid) and 'meso-gamma' (5km grid) analyses are generated (Andersson *et al*, 1986) to provide initial fields for simplified forecast models, and the wind field near the surface is calculated by a small area model. Satellite data are processed by a special subsystem called PROSAT (Liljas, 1990; Karlsson and Liljas, 1990) to produce a variety of derived products as images on a range of scales, including cloud classifications and estimates of precipitation.

VSR forecasts of many weather elements are produced, including wind, temperature, humidity, cloudiness, precipitation and thunder. The system employs several forecasting techniques, including specialized numerical models, though a full 3-D NWP model is not included because of the large computing resources it would require and the operational demand on the system for speed. Nowcasts of precipitation and thunderstorms are based on Doppler radar and lightning-location observations. Rainfall patterns may be extrapolated with velocities derived from cross-correlation of successive images or moved with Doppler-measured winds, and rainfall forecasts are given as probabilities. Sea-surface pressure is forecast using a vorticity-advection model and an air-mass transformation model is used for boundary-layer variables (Gollvik and Omstedt, 1988).

The workstation is designed for flexibility and ease of use. It handles some 3000 images/day, and this is expected to increase. Display options include overlaying, zooming and variable-speed animation. The forecaster controls the system, selects functions and interacts with the displayed data using a combination of mouse, data-tablet and keyboard. Options are selected by menu or (for commonly used products) predefined 'direct-function' keys.

Drawing and annotation facilities allow image and graphics products to be prepared for customers, though a separate production system is intended for this task. The philosophy behind PROMIS 600 is that as far as possible the tailoring of products and their delivery to customers should be done automatically, freeing the forecaster to concentrate on the mesoscale forecasting problem. Automatic generation of spoken forecasts, for access by telephone, and direct transmission of images and other data to customers' computers have been implemented.

4.2 Automation

Much effort is being put into automating tasks within VSRF. However, the extent to which automation is necessary, possible or desirable is a matter of some debate (Doswell, 1991).

From the start, computers have been indispensable elements in VSRF for the routine data-handling tasks associated with gathering, processing and presenting mesoscale observations. More controversial, and difficult, is the automation of the interpretive and judgemental tasks that go into analysing the data in meteorological terms, recognizing and correcting errors, and producing a forecast.

There are several reasons for wanting to automate VSRF.

- Cost. Processing rapidly changing mesoscale data interactively, as for example in the FRONTIERS precipitation nowcasting system (§3.2.2), can be an intensive, full-time task, and to do this 24h/day requires a roster of four or five forecasters. Thus although the capital outlay on an automatic system may be large, its running costs can be much lower than those of a manned system.

- Speed. The human forecaster can have difficulty keeping pace with the flow of detailed, real-time information, particularly in active weather situations or if many corrections have to be made to the observational data. The problem is becoming more acute as operational forecasting is extended to very short-lived phenomena,

with only a few minutes from the first signs to the event itself. The likelihood is that automatic systems can be made fast enough to cope (given the ongoing rapid increase in the power/price ratio of computers), provided that the problems of *how* to perform the tasks automatically can first be solved.

- Production of tailored local forecasts. The essence of VSRF is the provision of detailed local forecasts, tailored to the needs of individual users. The speed and cost factors described above mean that it will be difficult or impossible to provide these to numerous different users without automation.

- Repeatability. Objective (automatic) procedures are repeatable: the same data will always produce the same result.

- Quality. Objective forecasts offer the eventual prospect of being better than subjective (manual) forecasts in that their repeatability, and the ability to run through series of archived cases to test improvements to algorithms, provide a path to make consistent improvements.

Those sceptical of the promised benefits of automation suggest however that it carries significant dangers; in particular that increased routine reliance on technology will erode the skill of forecasters, making them less able to add value to forecasts and therefore, in turn, strengthening the arguments for more automation.

The view is also often expressed that even successful automatic systems will need to be supervised by experienced human forecasters who can recognize and compensate for errors, modifying, or at least being allowed to veto, automatically generated products.

There already exists a commitment to automation in many current and planned programmes. For example, the Terminal Doppler Weather Radar (TDWR) system (§5) must run and provide warnings unattended, and work is underway to automate the FRONTIERS precipitation nowcasting system at the UK Meteorological Office.

It is unlikely that the trend towards automation will be reversed. Attention will therefore need to be given to managing it in such a way as to avoid the pitfalls as far as possible.

4.2.1 Artificial intelligence

Many forecasting and data-interpretation tasks rely on the experience and judgement of human forecasters. This is particularly true in VSRF which often depends critically upon pattern recognition and the use of conceptual models. This has prompted attempts to use artificial intelligence (AI) techniques to help understand and automate these functions.

AI processes are used to perform interpretive and decision-making functions; often they are used to control and select numerical processes in the same way that a human operator might in an interactive system.

AI is not a single technique but many. In a knowledge-based ('expert') system, knowledge about a problem area ('domain') is expressed explicitly, often in the form of IF... THEN... rules. An alternative formalism ('frames'), in which objects are described in terms of lists of attributes whose values vary from one instance to another, lends itself

quite naturally to the representation of conceptual models. Although numerical values and relations are often used, a characteristic of AI systems is the representation of knowledge in symbolic form (in terms of named objects), and use of qualitative relations. Conway (1989) provides an introduction to some of these ideas in the context of weather forecasting. Early expert systems tended to employ empirical rules to make forecasts, but more recently the trend has been to try to use so-called 'deep knowledge', which represents the causal mechanisms that underlie events, and thus to construct systems that are less brittle and that are not specific to a particular geographical location (Dyer, 1989).

Neural networks (see, for example, Lippmann, 1987) are a branch of AI receiving much attention at the moment. They consist of networks of nodes and links which may be realized in hardware or simulated in software. The nodes are simple processors each of which generates an output value that depends in some way on the sum of its inputs. A link connects the output of one node with the input of another, and programming the network consists of setting or adjusting the strengths of the (many) links. Input values are presented to the network at selected nodes and other nodes deliver the output of the network. (For example, inputs could be parameters characterizing a region of a satellite image and outputs could be a code for the likely cloud type in that region). Programming the network is usually done by presenting it with a large number of training examples and using an algorithm that adjusts the strengths of the links until the network consistently approximates the desired response, whereupon it is regarded as 'trained' and may be applied to new cases outside the training set.

Neural networks are the subject of intensive research, and many problems remain, but they appear to hold promise in pattern recognition and classification tasks. A difficulty that may inhibit their acceptance is that the knowledge embedded in a trained network is not explicit, a situation that some find unsatisfactory.

AI systems are being applied widely in meteorology. Although many have been specifically developed for VSRF applications, other areas have also received attention. The underlying techniques are often not specific to a particular forecasting regime and so the examples below are not exclusively from VSRF.

Example applications of knowledge-based systems (KBS) are the analysis of Doppler radar data (Campbell and Olsen, 1987; Moninger, 1988) and of satellite imagery (van der Lubbe *et al*, 1990). Attempts are also being made to use AI techniques to automate synoptic analyses of surface data and NWP output, with the intention of extending this work to a wide range of data types and meteorological objects (Sénési *et al*, 1990). KBS have been applied to forecasting visibility (Stunder *et al*, 1987; Tremant, 1989), low cloud (Desmarais *et al*, 1991), precipitation (Neumann and Einfalt, 1990; Dai Honghua *et al*, 1987), frost and road-ice (Takle, 1990) and strong winds (Weaver and Phillips, 1990). Many systems have been developed for forecasting convection and associated phenomena (e.g., Weaver and Phillips, 1987; Merrem and Brady, 1988; Roberts, 1988; Passner and Lee, 1990); one of the most sophisticated of these is the Knowledge Augmented Severe Storms Predictor (KASSPr) (Bullas *et al*, 1990) developed by AES, Canada, which has evolved from earlier systems and is undergoing limited operational trials. The Canadian weather service is also experimenting with systems for the automatic generation of forecast text (Goldberg *et al*, 1988; Paterson and McLeod, 1991; Morrissey, 1991); given forecast values for the appropriate meteorological elements, the systems are designed to produce worded forecasts, suitable for issuing to the public, in both English and French.

Interest in neural networks has a shorter history, but they are being applied to such tasks as lightning prediction (Frankel *et al*, 1989), the analysis of satellite cloud imagery (Lee *et al*, 1990; Peak and Tag, 1991; Smotroff *et al*, 1991), precipitation forecasting (Webb, 1990) and retrieval of interferometer sounding data (Lure *et al*, 1991).

Most AI systems are experimental, but a few are reaching the stage of limited operational trials. NOAA's FSL has sponsored two summer intercomparison exercises, "Shootout '89 and '91" (Moninger, 1990) during which several independently developed AI systems were used to make daily forecasts of the likelihood of severe convective weather in a region of NE Colorado. The purpose of the exercises was not to find winners and losers but to help gain an understanding of the strengths and weaknesses of different approaches. Part of their significance is that there were enough groups developing AI systems concerned with convection to make such exercises viable.

The application of AI techniques to weather forecasting is the subject of vigorous research and rapid development, and exchange of ideas among participants is important for progress. The AIRIES (Artificial Intelligence Research In the Environmental Sciences) series of workshops (Dyer and Moninger, 1988) have been important in bringing workers in the field together, and there is now sufficient interest in the subject for many meteorological conferences to include AI sessions.

5 Convection, and extremely short-range forecasts

Examples in the foregoing sections, while by no means comprehensive, have perhaps indicated the wide range of weather events to which VSRF is being applied. All these applications are important; however, the application of VSRF currently receiving more attention than any other is the analysis and forecasting of convective storms and associated weather events. These are of obvious importance in regions prone to severe tornadic storms, but they are also significant in other places for events such as heavy precipitation, lightning and hail. They are below the scale resolved by current NWP models and often quickly diverge from linear extrapolations. The CAPS programme (see §3.1) aims to model severe storms numerically; other approaches showing promise are based on relating high resolution radar and satellite observations to conceptual models of convective development.

The rapid evolution of convective systems creates difficult forecasting problems. In order to provide users with as much warning as possible it is useful to be able to observe and recognize precursors to the events of interest, rather than just the events themselves, and this entails developing an understanding, usually in the form of conceptual models, of the important physical mechanisms at work.

Purdom (1982) showed that cloud arc lines on satellite images could reveal convergence zones produced by thunderstorm outflows, and mark preferred areas for the growth of new storms. Wilson and Schreiber (1986) demonstrated that convergence lines detected by radar in the clear-air boundary layer could be used in similar ways. These concepts were used in a recent series of experiments at Darwin, Australia, to make short-term forecasts of tropical thunderstorms (Keenan *et al*, 1992). Subjective forecasts based on the extrapolated movement of radar-observed convergence lines proved more skilful than either persistence or climatology up to 3h ahead.

For sites or activities sensitive to specific weather events, such as microbursts or lightning, warnings of as little as a few minutes may be useful, provided that they are sufficiently precise and reliable. Roberts and Wilson (1989) developed three conceptual models of microburst generation in storms and demonstrated the possibility of producing warnings of 0–10 minutes based on Doppler radar observations. Eilts *et al* (1991) describe experiments to generate thunderstorm forecasts, based mainly on radar observations, at Kennedy Space Center. The most reliable indicator was found to be a radar echo of strength $\geq$10dBZ, near the freezing level and above a surface-based convergence boundary. Such a signature was found to precede the first lightning strike to ground by an average of 13 minutes.

The Terminal Doppler Weather Radar (TDWR) programme (Evans, 1991; Wieler and Shrader, 1991) is designed to improve the safety and availability of airports in the United States by providing warnings of low altitude wind shear. (See TDWR (1991) for papers on various aspects of the system; Brylyov *et al* (1991) outline approaches to the automatic identification of hazards at airports in the former USSR).

The principal meteorological requirements of TDWR are reliable microburst detection, with *warnings of at least one minute* to pilots; detection of gust fronts, with 20-minute warning of gust front arrival and forecast of the wind velocity (speed and direction) after passage of the front; and measurement of precipitation to a range of 90km.

Detection is by means of a single Doppler radar sited (ideally) in line with the runway at a distance of about 15km. The system is required to run unattended and to provide the required warnings automatically, direct to air traffic control staff, without the need for further meteorological interpretation. Its output will be integrated with the anemometer-based low-level wind shear alert system (LLWAS) currently in operation at many US airports (Wilson and Gramzow, 1991).

The TDWR thus brings together, in a single system, several current developments in VSRF: operational use of VSRF at extremely short lead times (down to 1-minute), operational use of meteorological Doppler radar, automatic recognition of events and provision of warnings, and integration of products from diverse observational systems. It has only become possible because of the sorts of advances in observing systems, communications, computing resources, automation and conceptual models that have been described in earlier sections of this review. Planned enhancements to the TDWR system will involve further extensions in several of these areas.

6 Verification

Rapid developments in VSRF, with many new ideas and competing techniques being investigated, make forecast verification and assessment more important than ever. Automatic, adaptive combination of forecasting methods (§3.8) depends upon the availability of effective methods of assessing and comparing candidate forecast contributions. Forecasting experiments need careful design and clearly stated aims (e.g., Doswell and Flueck, 1989) to enable meaningful verification to be performed.

There is no shortage of statistical measures of forecast accuracy, but little consensus regarding their use. Summary scores can tell only part of the story; if assessment methods

are to guide developments they must not only measure overall success but also indicate the nature of the errors. Stanski *et al* (1989) provide a critical survey of verification methods in meteorology, including the commonly-used skill scores and the role of subjective assessment.

7 Conclusions

The VSRF task is to provide frequent, detailed, local weather forecasts. It consists of making observations, interpreting them, producing the forecast, tailoring it to the user's requirements and delivering it, all within a period that may be as little as a few minutes, and then (usually) repeating this cycle. Developments and improvements are currently underway in all aspects of the VSRF process; the following seem particularly worthy of note.

- Remotely-sensed observations are of particular importance to VSRF. Considerable progress is being made in establishing new and improved observing systems and techniques, in international exchange of mesoscale observations, and in objectively combining mesoscale observations from many diverse sources.
- Powerful interactive facilities for displaying, analysing and manipulating an ever-increasing variety and volume of data are being developed and installed in forecast offices. At the same time, efforts are being made to apply automation, including the use of artificial intelligence techniques, to all stages of the VSRF process. This is a particularly challenging task because many current VSRF applications depend upon the pattern-recognition capabilities and meteorological knowledge of experienced forecasters.
- Conceptual models of mesoscale weather systems are being developed and used to interpret observations and relate them to subsequent events. They may be used either by human forecasters or in automatic systems, and also offer a way of linking observed parameters to NWP model variables.
- Although VSRF is being applied to many phenomena, convective storms and their associated weather events are the largest single preoccupation. They are not resolved by current NWP models and diverge rapidly from linear extrapolation, but promising attempts are being made to apply conceptual models in this area, and work is underway to develop suitable, very high resolution, numerical forecast models.
- Extremely short-range forecasts are being attempted in situations such as microbursts where only a few minutes elapse between the first signs and the event itself. Such applications provide a severe test of all components of the VSRF process, the spur to progress being their importance both economically and for human safety.
- Integrated forecasting systems that combine different methods in an adaptive, situation-dependent way offer the prospect of improved VSRF by using the various forecast methods to their best advantage. Effective verification and evaluation techniques are

essential, both as components of such systems and in order to guide the development of forecasting procedures, particularly automatic ones.

8 Acknowledgements

I wish to express my gratitude to the many people who have helped in the preparation of this review by sending me information about their work and that of their colleagues and by offering suggestions and opinions, and to apologise if, through oversight, misunderstanding or lack of space, I have failed to do justice to their efforts.

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